igneous rock running through horizontal strata *s*. If we saw merely the horizontal portion below or above, the really igneous and intrusive nature of the rock *t* might escape us, but the intermediate connecting vein makes its character at once apparent.

No rock exhibits so admirably as granite the varieties assumed by veins. In many cases the veins which traverse the granite itself must be regarded as segregation or infiltration veins, as already described. But where they proceed from the granite, and traverse surrounding rocks, they are probably in most cases intrusive, though where granite and highly granitic gneiss are in contact we may conceive that some of the veins traversing both rocks may be segregation veins. Most large masses of granite send veins into the surrounding rocks. Frequently the veins so abound as to form a complicated net-work. They vary in breadth from several feet or even yards down to fine filaments at the ends of the smaller branches. They frequently cross each other, not only outside of the granite mass, but even within it. They vary much in texture and in composition. Sometimes they are coarsely crystalline; but probably most of the veins of this kind are due rather to segregation than intrusion. Most frequently granite veins traversing granite are finer-grained than the main mass. Veins which are clearly intrusive are not only finer in grain than the parent granite, but sometimes present considerable differences in mineralogical composition. The mica, for example, may be reduced to exceedingly minute and not very abundant flakes, and may almost disappear. The quartz also occasionally assumes a subordinate place, and the rock of the veins passes into eurite, elvanite, or one of the varieties of porphyry.

The rocks surrounding a granite mass and traversed by granite veins are almost always more or less metamorphosed in a belt varying in breadth from a few yards up to a mile or more. It is in this zone that the granite veins typically occur. The altered rocks have assumed the characters of gneiss, mica-schist, or other metamorphic product, but resume their usual condition as we trace them away from the granite. Curious angular portions of them may often be observed within the granite veins and in the main granite mass. In Cornwall the granite and surrounding slates are traversed by veins of quartz-porphyry termed *elvans*, which are most numerous near the granite. They vary in width from a few inches or feet to 50 fathoms, their central portions being commonly more crystalline than the sides. In the great granite region of Leicester Mr Jukes traced some of the elvans for several miles running in parallel bands, each only a few feet thick, with intervals of 200 or 300 yards between them. Many of the other intrusive rocks likewise present the phenomena of veins; diorite, diabase, melaphyre, and basalt furnish numerous illustrations.

*Dykes* are wall-like masses of igneous rock, filling vertical or highly-inclined fissures. They differ therefore from veins in the greater parallelism of their sides, their verticality, and their greater regularity of breadth and persistence of direction. They present as great a variety of thickness as that which is shown by veins. Sometimes they occur as mere plates of rock not more than an inch or two in thickness; at other times they attain a breadth of ten or twelve fathoms. The smaller or thinner dykes can seldom be traced more than a few yards; but the larger examples may be followed sometimes for miles. Thus in the south of Scotland a remarkable series of basalt-dykes can be traced across all the geological formations of that region and even across powerful faults. They run parallel to each other in a general north-west and south-east direction for distances of 20 and 30 miles. A remarkable dyke crosses the north of England from the coast of Yorkshire for fully 60 miles inland.

The name dyke is applied to these masses of igneous rock on account of their resemblance to walls (*Scotice*, dykes). Their sides are often as parallel and perpendicular as those of a piece of masonry. Moreover, the resemblance to human workmanship is sometimes brought out still more by the numerous joints which, intersecting each other along the face of a dyke, remind us of well-fitted masonry. Where the surrounding rock has decayed, the dykes may be seen projecting above the ground exactly like walls; indeed in many parts of the west of Scotland they are made use of for enclosures. The material of the dykes has in other cases decayed, and deep ditch-like hollows are left to mark their sites. The coast-lines of many of the Inner Hebrides and of the Clyde Islands furnish numerous admirable examples of both kinds of scenery.

While veins have been injected into irregular branching cracks, dykes have been formed by the welling upwards of liquid rock in vertical or steeply inclined fissures. Sometimes the line of escape has been along a fault. In Scotland, however, which may be regarded as a typical region for this kind of geological structure, the vast majority of dykes rise along fissures which have no throw, and are therefore not faults. On the contrary the dykes may be traced across some of the largest faults in the midland counties.

While the term dyke might be applied to some of the wall-like intrusions of porphyry, elvanite, and even of granite, it is more typically illustrated among the augitic igneous rocks, such as basalt, diabase, &c., though also among diorites, porphyries, pitchstones, &c. The central parts of a dyke are usually most crystalline. Towards the margin the grain becomes finer, and even sometimes passes into a vitreous condition. Many of the basalt dykes in different parts of Scotland are coated along the sides with a film or crust of black vitreous tachylite. Lines of amygdaloidal kernels may not infrequently be traced along the centre of a dyke.

When the rock on one side is freshly stripped off, the dyke is usually observed to present a system of polygonal jointing. The joints start from each face or cheek, and either go right across to the opposite side, or branch and lose themselves about the centre. They thus divide the dyke into irregular prisms which, when the dyke is vertical, lie of course in a horizontal position, whence they depart in proportion as the dyke is inclined. Occasionally the prisms are as well-formed as in any columnar bed of basalt. A less prominent set of joints runs parallel with the two cheeks of a dyke.

There is usually some alteration of the stratified rocks in contact with a dyke; but the nature and amount of the change vary within a wide range. The most sensitive material to this influence is undoubtedly coal. A seam of coal 6 or 8 feet in thickness may be observed to grow dull and brittle at a distance of 50 yards from a large dyke, becoming what is termed "blind coal," as it then burns without flame. Still nearer to the intrusive mass the coal passes into a kind of pyritous cinder scarcely half the original thickness of the seam. At the actual contact with the dyke it becomes by degrees a kind of caked soot not more perhaps than a few inches thick. Sandstones are hardened into a kind of lustrous quartzite, and sometimes made columnar, shales into flinty slate or porcellanite; limestones are occasionally rendered crystalline and even dolomitic. Occasionally a segregation of new minerals has taken place in the rocks adjoining a dyke. But cases are by no means infrequent where dykes have produced little or no appreciable change upon the contiguous rocks.

IV. Necks.—Under this term are included the filled-up pipes or funnels of former volcanic vents. Every series of volcanic sheets poured out at the surface must have been

connected with one or more orifices which, on the cessation of the eruptions, would remain more or less completely filled with lava or with fragmentary matter. But unless subsequent denudation should remove the overlying cone and its surrounding piles of lava and tuff, these vents must remain buried under the materials which came out of them. So extensive, however, has been the waste of the surface in many old volcanic regions that the sites of the vents have been laid bare. In the study of these we have before us some of the more deep-seated phenomena of volcanic action never to be seen in any modern volcano.

A neck is of a circular or elliptical, but occasionally of a more irregular branching form. It varies in diameter from a few yards up to a mile, or even more. It descends into the earth perpendicularly to the stratification of the formation to which it belongs. Thus, if a neck was formed and filled up during the accumulation of a certain group of strata, it would rise on the whole vertically through these strata, and its ejected lava or tuff would spread out conformably among them. Should the rocks be subsequently tilted the neck would of course be thrown out of the vertical. As a rule, however, the vertical descent of the necks into the earth's crust has been comparatively little interfered with.

The materials filling up ancient volcanic orifices are sometimes crystalline, sometimes fragmental. The neck may be occupied by some form of lava, as felstone, quartz-porphyry, diabase, porphyrite, basalt; or by the fragmentary materials which fell back into the throat of the volcano and finally solidified there; or by both kinds of rock combined. Among the Palæozoic volcanic districts of Britain the necks not infrequently are filled with some siliceous crystalline rock, such as a quartz-porphyry or felstone, even where the surrounding lavas are basic. Necks of agglomerate and fine tuff abound among the Carboniferous and Permian volcanic regions of Scotland.

The fragmentary materials consist mainly of different lava-form rocks imbedded in a gravelly *peperino*-like matrix of more finely comminuted debris of the same rocks; but they also contain, sometimes in abundance, fragments of the strata through which the necks have been drilled. Pieces of fine stratified tuff not infrequently appear in the agglomerates. This fact, coupled with the not uncommon occurrence of a tumultuous fractured and highly-inclined bedding of the materials in the necks, appears to show that the pipes were partly filled up by the subsidence of the tuff consolidated in beds within the crater and at the upper part of the funnel. Veins of basalt abound in many of the necks of Carboniferous age in central Scotland.

The strata round a neck are usually somewhat hardened. The sandstones have acquired sometimes a vitreous lustre; argillaceous beds have been indurated into porcellanite; coal-seams have been burnt and rendered unworkable. These changes may be due partly to the heat of the ascending column of molten rock or ejected fragments, partly to the ascent of heated vapours, even for a long time subsequently to the volcanic explosions. Proofs of a metamorphism probably due to the latter cause may sometimes be seen within the area of a neck. It is where the altered materials are of a fragmentary character that the nature and amount of this change can be best estimated. What was originally volcanic dust has been converted into a crystalline and even porphyritic mass, through which, however, the likewise intensely altered blocks interspersed through the agglomerate are still recognizable. Such blocks as, from the nature of their substance, must have offered most resistance to change,—pieces of sandstone or quartz, for example,—stand out prominently in the altered mass, though even they have undergone more or less modification, the sandstone being converted into vitreous quartz-rock.

## *Section II.—Volcanic, Interbedded, or Contemporaneous Igneous Rocks.*

The rocks comprised in this section have all been ejected to the surface like the lava-streams and showers of ashes of modern volcanoes. It is evident that on the whole they must agree in lithological characters with those rocks, described in the previous section, which have been extravasated by volcanic efforts though not quite reaching the surface. Yet they have some well marked general characters, of which the most important may be thus stated. (1.) They occur as beds or sheets which conform to the bedding of the strata among which they are intercalated. (2.) They do not break into or involve portions of the overlying beds. (3.) The upper and under portions of the lava sheets present commonly a scoriaceous or vesicular character, which may even be found extending throughout the whole of a sheet. (4.) Beds of tuff are frequently interstratified with the crystalline sheets.

I. Crystalline.—While the underground course of a protruded mass of molten igneous rock has widely varied according to the shape of the channel through which it proceeded, and in which, as in a mould, it solidified, the behaviour of the rock, once poured out at the surface, has been much more uniform. As in modern lava, the erupted rock has rolled along, varying in thickness and other minor characters, but retaining the broad general aspect of a bed or sheet. A comparison of such a bed with one of the intrusive sheets already described shows that in several important respects they differ from each other. An intrusive sheet is closest in grain near its upper and under surfaces. A contemporaneous bed or true lava-flow, on the contrary, is there usually most open and scoriaceous. In the one case we rarely see vesicles or amygdules, in the other they often abound. However rough the upper surface of an interbedded sheet may be, it never sends out veins into nor encloses portions of the superincumbent rocks, which, however, sometimes contain portions of it, and wrap round its hummocky irregularities as shown in fig. 57. Occasionally it may be observed to be full of rents which have been filled up with sandstone or other sedimentary material. In these cases we see that the lava cracked in solidifying, and that sand was washed into the fissures where it consolidated. The amygdaloidal cavities throughout an interbedded sheet, but more especially at the top, may often be noticed with an elongated form, and even pulled out into tube-like hollows in one general direction, which was obviously the line of movement of the yet viscous mass.

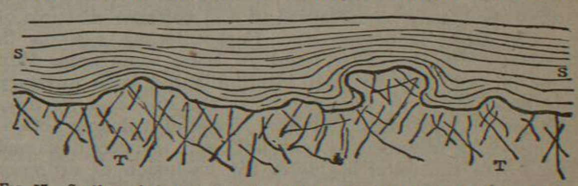

Fig. 57.—Section of the upper surface of an interbedded sheet T, showing how its unevennesses are wrapped round and covered by the sedimentary rocks S.

Some kinds of rock when occurring in interbedded sheets are apt to assume a system of columnar jointing. Basalt in particular is distinguished by the frequency and perfection of its columns. The Giant's Causeway and the cliffs of Staffa, of Ardtun in Mull, and of Loch Staffin in Skye are well-known examples. The columns are set perpendicularly to the two cooling surfaces, that is, to the top and bottom of the bed. Any inclination from the horizontal in the disposition of the bed will cause a corresponding departure from the vertical on the part of the columns. Sometimes the columns are arched or curved, as in the Clam-shell Cave, Staffa.

A single interbedded sheet of crystalline rock seldom occurs by itself without any other volcanic accompaniment. It is usually associated at least with bands of tuff showing that the emission of lava was not unattended with fragmentary ejections. In the majority of cases it will be found to form part of a series of interbedded sheets with intercalated tuffs. Vast piles of such consecutive flows, reaching a total depth of several thousand feet, remain to witness the energy of former volcanic vents.

II. Fragmental.—The rocks embraced under this term include all the fragmentary volcanic ejections which enter into the composition of the earth's crust, from the coarsest agglomerate to the finest tuff. They differ in lithological character, according to the nature of the lavas with which they are associated and from which they have been derived. Thus in a region of trachyte-lavas, we have trachyte-tuffs, trachyte-breccias; in one of basalts, we find basalt-breccias, basalt-agglomerates, basalt-tuffs; in one of obsidians, we meet with pumiceous tuffs and breccias. The fragmentary matter has been ejected from volcanic vents, and has fallen partly back into the funnels of discharge, partly over the surrounding area. It is therefore apt to be more or less mingled with ordinary sedimentary detritus. We find it indeed passing insensibly into sandstone, shale, limestone, and other strata.

Great differences occur in the texture of fragmental rocks even in the same volcanic districts. They are often coarse and tumultuous at or near the vents, and fine-grained at a distance. Alternations of gravelly *peperino*-like tuff with a very fine-grained "ash" may frequently be observed. Large blocks of lava-form rock, as well as of the strata through which the volcanic explosions have taken place, occur in the tuffs of most old volcanic districts.

It has been already pointed out that agglomerate and tuff are not infrequently to be met with occupying the sites of the vents of eruption. Their most common disposition, however, is in beds either alone or associated with interbedded lavas. Masses of fine or gravelly tuff several hundreds of feet in thickness, without the intervention of any lava-bed, may be observed in the volcanic districts of the Old Red Sandstone and Carboniferous systems in Scotland. On the other hand, in these same areas thin seams of tuff may be seen interlaminated with ordinary sandstone, shale, or limestone. In the one case we have evidence of long-continued and powerful volcanic action, during which fragmentary materials were showered out and spread over the water-basins to the exclusion of ordinary sediment. In the other we have proof of feeble intermittent volcanic explosions, whereby light showers of dust were discharged, which settled down quietly amidst the sand, mud, or limestone accumulating around at the time. Under these latter circumstances tuffs often became fossiliferous; they enclose the remains of such plants and animals as might be lying on the lake-bottom or sea-floor over which the showers of volcanic dust fell, and thus they form a connecting link between aqueous and igneous rocks.

## VIII.—Metamorphic Rocks as Parts of the Architecture of the Earth's Crust.

In part ii. (*ante*, p. 235) some account has been given of the composition of certain foliated rocks frequently met with in the central portions of mountain chains and elsewhere, lying beneath geological formations of high antiquity. In part iii., in the discussion of the hypogene causes of change within the earth's crust, reference was again made to these rocks, and they were alluded to as examples of the effects of subterranean processes altering the original character of large mineral masses (*ante*, p. 263). They were there cited as *metamorphic* rocks, but their characters as integral parts of the earth's crust were reserved for discussion in the present part of this article.

At the outset some caution must be employed as to the exact meaning in which the terms "metamorphism" and metamorphosed" are employed. In a certain sense it may be said that all or nearly all rocks have been metamorphosed, since it is exceptional to find any, at least among such as are not in a geological sense of modern date, which do not show, when closely examined, proofs of having been altered by the action of percolating water or other daily acting metamorphic agent. Even a solid crystalline mass which, when viewed on a fresh fracture with a good lens, seems to consist of unchanged crystalline particles will usually betray under the microscope unmistakable evidence of alteration. And this alteration may go on until the whole internal organization of the rock has been readjusted, though the external form may still remain such as hardly to indicate the change, or to suggest that any new name should be given to the recomposed rock. Among many igneous rocks, particularly the more basic kinds, as basalts, diorites, olivine rocks, &c., metamorphism of this kind may be studied in all its stages.

But it is not to alteration of this nature, effected at the surface by meteoric water, that the term metamorphism is properly applied. That word is reserved for the process of subterranean change above treated of (*ante*, p. 258), whereby a more or less complete transformation has been effected throughout vast mineral masses which, while undergoing crystalline rearrangement, have usually suffered simultaneously enormous compression. Gneiss, mica-schist, and the other schistose or foliated rocks are typical examples of the results of this metamorphic process.

Three antagonistic opinions are at present entertained regarding the origin of these rocks. Some geologists regard the crystalline schists as plutonic rocks representing the early cooled crust of the earth, and suppose that a similar schistose structure has occasionally been superinduced by plutonic action on later sedimentary formations. Again, by some recent writers the Wernerian notion of chemical precipitation has been revived, and the idea of metamorphism has been discarded. These authors suppose that the schistose rocks, in common with many pyroxenic and hornblendic rocks (diabases, diorites, &c.), as well as masses in which serpentine, talc, chlorite, and epidote are prevailing minerals, have been deposited "for the most part as chemically-formed sediments or precipitates, and that the subsequent changes have been simply molecular, or at most confined in certain cases to reactions between the mingled elements of the sediments, with the elimination of water and carbonic acid." To support this view, it is necessary to suppose that the rocks in question were formed during a period of the earth's history when the ocean had a considerably different relative proportion of mineral substances dissolved in its waters, and consequently that they must be assigned to a very early geological period, anterior indeed to what are usually termed the Palæozoic ages. And it becomes further needful to discredit the belief that any gneiss or schist can by possibility belong to one of the later stages of the geological record. The more thorough-going advocates of the pristine or "eozoic" date and original chemical deposition of the so-called "metamorphic" rocks do not hesitate to take this step, and endeavour, by ingenious explanations, to show that the majority of geologists have mistaken the geological structure of the districts where these rocks have been supposed to be metamorphosed equivalents of what elsewhere are Palæozoic, Secondary, or Tertiary strata.[1] Prevalent opinion supports the third or metamorphic theory, according to which the schistose rocks are held to be crystalline transformations of ordinary sedimentary strata. The problem whether or not certain masses of gneiss or schist represent equivalent unaltered sedimentary rocks of other districts is mainly one of structural geology. It must be decided by the geologist rather than the chemist. It has been answered in the affirmative by the great majority of stratigraphical geologists all over the world. We may not be entitled to assert that every mass of gneiss or schist is a metamorphosed sedimentary rock. Possibly some foliated rocks of extreme antiquity may have originated directly from chemical precipitation. But when it can be shown that ordinary stratified rocks have been converted into schist and gneiss, it seems permissible to hold that all such rocks have had a similar origin, at least until good reasons can be adduced against that view.

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[1] See Sterry Hunt's *Chemical Essays*, p. 283 *sq.*

It is evident that if the so-called metamorphic rocks can anywhere be seen to graduate into unaltered strata, it is there that they ought to be specially studied, and that light may be expected to be cast on their origin and history. It is customary to speak of metamorphism as being either local or regional, that is, being confined to one limited portion of a mass of rock, or as extending throughout the whole of the rock and over wide districts. It is doubtless from the first of these developments that we may hope to learn most regarding metamorphic changes.

*Local (Contact) Metamorphism.*—The simplest and most obvious examples of this kind of alteration occur where a mass of igneous rock has invaded sedimentary strata, which have in consequence been affected in lithological character along the margin of contact with the intrusive rock. Allusion has already been made to changes of this kind effected by intrusive sheets and dykes, and likewise traceable round the edges of ancient volcanic vents. Sandstones are converted into a lustrous crystalline quartz-rock; shales and argillaceous strata are indurated into porcellanite, jasper, flinty-slate, or some analogous product. Limestones are made crystalline; coals are charred, turned into anthracite, and sometimes even into graphite. These metamorphisms extend to very variable distances from the intrusive rock. Sometimes they are scarcely perceptible at all, and disappear within a space of a few inches. In other cases they extend for some feet, and in the case of some coal-seams even to 50 yards or more.

It is around bosses of granite however that the most marked examples of local metamorphism can be observed. On a previous page some account has been given of the way in which the Silurian rocks of Ireland and the south of Scotland are pierced by large masses of granite, and how, as they approach the granite even at a horizontal distance of a mile or more, they begin to assume a micaceous foliated texture which becomes more and more marked until, along the margin of the granite, they pass into true mica-schist and gneiss. The identity of origin between these schistose masses and the greywackes and shales beyond the metamorphic zone does not admit of any question. The unaltered rocks can be followed step by step into and through the stages of alteration, until they are found to have acquired the genuine gneissic or schistose structure. Moreover, it may be observed that all the bands of sedimentary rock do not give rise to the same kinds of metamorphic products. Some kinds of strata are more prone to alteration than others, and give rise to more perfect schists. In the south of Scotland, for example, certain greywackes and grits formed of a granular mixture of quartz-sand, felspar, clay, and various decomposition products have been metamorphosed into perfect mica-schist, while some bands of black anthracitic and graptolitic shale have merely been intensely indurated and shattered. Many districts in Scotland, in Ireland, in the lake country of England, and in Wales might be cited as furnishing examples of this gradual conversion of ordinary sedimentary rocks into true schists.

*Regional Metamorphism.*—If then it can be proved that over limited areas thoroughly foliated rocks have been produced by the transformation of ordinary sedimentary strata, a presumption is established in favour of a similar mode of origin for foliated rocks elsewhere and over wider regions. There occur many vast spaces of the earth's surface occupied by foliated rocks. In Finland, Scandinavia, and the Scottish Highlands tracts many thousands of square miles in extent consist of gneiss, mica-schist, hornblende-rock, and other members of the same great family of rocks. A large portion of British North America lies upon similar mineral masses. Rocks of this type commonly rise also along the core of great mountain ranges, as in the Alps and in the Rocky Mountains. If these rocks which cover such vast areas were originally ordinary sedimentary rocks, they must have been metamorphosed, not by mere local protrusions of igneous matter, but by some general process.

*Gradations of Metamorphism.*—We have seen above that the nature and extent of the alteration experienced by rocks have been regulated, not merely by the vigour of the metamorphic process, but by the composition and structure of the rocks themselves. A siliceous sandstone, for instance, containing little or no aluminous or other admixture, seems to be capable of retaining much of its original character, while surrounding or intercalated less purely quartzose beds have been completely changed. It is converted into quartz-rock, but still shows the rounded quartz grains of the original sand. In proportion as the sand has been mixed with clay it has produced a rock more susceptible of change. The argillaceous (or magnesian) cement has been attacked, and in the process of change the quartz-sand has been affected. Mica in one or other of its various forms, aluminous or magnesian, has very generally appeared, and in proportion to its development has the foliated structure been made apparent. Hence we may obtain every gradation from a quartz-rock or grit into a true mica-schist or gneiss.

*Production of Foliation.*—The term "foliation" means the separation of a rock into approximately parallel or lenticular crystalline layers or folia of different mineral composition. It implies a segregation and crystallization of mineral matter along distinct planes. Those who maintain the original chemical precipitation of the most ancient gneisses and schists believe that the folia mark the stratification of the successive layers of deposit. Those, on the other hand, who hold that all the schistose rocks about the origin of which any satisfactory conclusion can be reached were originally mechanical sediments of ordinary kinds, regard the folia as coincident generally with the stratification of these sediments.

The folia of a gneiss or schist are crystalline aggregates which along their planes of mutual contact are as it were welded or felted into each other by the interlacing of their several component crystals. They are destitute, as a rule, of the parallelism, flatness, and persistence so characteristic of stratification. On the contrary they are apt to swell out into thick concretionary aggregations and to die out rapidly; they exhibit a wavy, crumpled, or puckered arrangement traceable in vast folds on the side of a mountain, and yet descending even to such minute corrugation as can only be detected by the microscope.

Foliation occurring in altered sedimentary rocks must be due to a crystallization and rearrangement of the chemical constituents of these rocks along certain lines. On a former page (*ante*, p. 263) it was pointed out that this kind of metamorphism would as a rule proceed along the lines of stratification. Doubtless in the vast majority of cases the planes of foliation are coincident with the general direction of this stratification. The metamorphic rocks of the Scottish Highlands furnish admirable proofs of this fact. Bands of quartz-rock and schist alternate with each other and with zones of limestone, precisely as beds of sandstone, shale, and limestone do in unaltered formations. Thin seams of pebbly grit with well-rounded water-worn pebbles may be observed running parallel with the folia of a schist, as a seam of fine grit or conglomerate may be seen to do in a series of shales. Nay, even the false-bedding so characteristic of mechanical sediment may be observed among these metamorphic rocks. The metamorphism is not uniform in these regions. Here and there it becomes intensified, and the rocks assume a thoroughly crystalline and much disturbed aspect. But as they recede from these areas they are found to lose much of their foliated character, and indeed to present such slight traces of metamorphism that they can be at once recognized as greywackes, grits, and shales. Moreover, they have been thrown into anticlinal and synclinal folds, and in these and other larger features of geological structure they differ in no essential respect from ordinary unaltered strata. Lastly, fossiliferous limestones containing Silurian shells have been found at their base, so that they have all been formed long after the seas over the area of Britain had been tenanted by living organisms.

Professor Sedgwick and Mr Darwin pointed out many years ago that a crystalline rearrangement of mineral matter has in some cases taken place along the planes of cleavage. We have already observed that the water which has been the great agent of metamorphism must always have followed the dominant divisional planes of a rock. If these planes were those of cleavage, the foliation would doubtless be produced along them, irrespective of the original laminæ of deposit. So long as the rock remained tolerably homogeneous in chemical composition, there seems no reason why foliation along the cleavage should differ in any material respect from that along stratification. But it may be doubted whether a cleavage foliation could run without sensible and even very serious interruptions over wide areas. For, in the first place, in most large masses of sedimentary matter we encounter alternations of different kinds of sediment, which could not but produce distinct kinds of rock under the influence of metamorphic change. In the second place, cleavage depends for its perfection and continuity on the fineness of grain of the rock through which it runs. While exceedingly perfect in a mass of argillaceous strata, it becomes feebler or even dies out in a coarse sandy or gritty rock. Hence, where foliation coincides with cleavage over large tracts, there will almost certainly be bands, more or less distinct, coincident with the original stratification, and running oblique to the general foliation, like bedding and cleavage, save where these two kinds of structure may happen to coalesce.

In a region of intense metamorphism the foliation of the schists may be observed to become here and there somewhat indefinite, until it disappears altogether, and the rocks assume a thoroughly granitic character. Between gneiss and granite there is no difference in mineralogical composition; in the one rock the minerals are arranged in folia, in the other they have no definite arrangement. Gneiss might be called a foliated granite; granite might be termed a non-foliated gneiss. The two rocks may be observed to graduate into each other. In Aberdeenshire, for example, the common grey mica-schist and gneiss may be seen to pass insensibly into the ordinary grey granite. In such cases it has been naturally concluded that granite is the ultimate stage of metamorphism. Judged merely from their composition and microscopic structure, an intrusive granite connected with igneous protrusions and a metamorphic granite representing the thorough transformation of stratified rock cannot be distinguished from each other.

There is thus nothing improbable in the idea that the same mineral particles may have gone through many successive cycles of change. We may suppose them to have been originally part of a granite mass, and to have been subsequently exposed at the surface by enormous denudation. Worn away from their parent granite they would be washed down with other particles, and spread out under water as parts of sandy or muddy deposits. Buried under a gradual accumulation of sedimentary material thousands of feet in thickness they might be depressed deep beneath the surface, and be thus brought within the influence of metamorphism. Gradually recomposed, crystallized, and converted into schistose rock, they might be eventually reduced to the condition of granite, and protruded into some of the overlying less metamorphosed masses in the form of granite veins. Or we may conceive, as already (*ante*, p. 309) suggested, that a communication was opened between the granite thus produced and the surface, and that the original mineral particles, whose vicissitudes we have been tracing, were erupted to the surface as part of a stream of lava.

*Possible Metamorphism of Igneous Rocks.*—In most large tracts of foliated rocks there occur masses less distinctly foliated or quite granitoid in texture, formed mainly of hornblende or of that mineral in combination with others. Zones or bosses of hornblende-rock and hornblende-schist frequently appear among gneiss and mica-schist. Varieties of quartz-porphyry occur in a similar way. Bands of fine unctuous chloritic schists may also often be traced. It is not easy to understand how such rocks, at least those containing a large percentage of magnesia, could be produced by the metamorphism of ordinary sediment. The difficulty may perhaps be removed if we regard them as having originally been igneous rocks, either erupted at the surface or intrusively injected among the surrounding rocks previous to metamorphism. Such mineral masses as varieties of syenite and diorite, rich in hornblende or other magnesian silicates, might have been the original condition of many of the rocks here referred to. The fine magnesian schists might be regarded as having been at first tuffs associated with the lava-form masses.

*Structure of Metamorphic Rocks in the Field.*—As the series of metamorphic rocks ranges from scarcely altered sedimentary strata on the one hand to crystalline amorphous granitic masses on the other, they must obviously possess a great range of structure as parts of the architecture of the solid land. In particular they must under different circumstances present the features now of aqueous and now of igneous rocks. The most typical form of metamorphism being foliation, we may consider the structure of foliated rocks as the most characteristic. From what has been said above, it is evident that the planes of foliation give the rocks a general resemblance to stratified sedimentary masses. But these planes are seldom so definite and persistent as those of stratification. They do not impart to the rocks the same tendency to split up into well-marked parallel beds. On the contrary they are often so felted or welded together, especially in the coarse and most crystalline gneisses, that they hardly serve as divisional planes at all, but leave the firm tough rock to split up along other lines.

With care and patience lines of anticlinal and synclinal fold may often be traced among foliated as well as among unaltered rocks. But the unravelling of these and other features of structure is much more difficult than among ordinary stratified formations. This arises partly from the frequent absence of conspicuous and persistent bands which could be used as horizons in working out geological

structure, partly from the abundant crumpling which most foliated rocks have undergone, whereby the continuity of the individual bands is much disturbed or entirely destroyed.

The joints among foliated rocks to which the regular and parallel folia impart a marked fissility resemble those among sedimentary strata. Where, however, the foliation is of a more massive kind, as in the coarser varieties of gneiss, the system of jointing approximates to that of granite or one of the more crystalline igneous rocks.

## IX. MINERAL VEINS.

The fissures which so abundantly traverse the crust of the earth have in many instances served as places for the deposit of mineral matter quite distinct from that of the rocks through which they run. As metallic ores frequently occur among the minerals so deposited, and have been extensively worked, a large amount of information has been obtained by mining operations regarding these fissures, or, as they are termed, *mineral veins*. A general though not invariable relation exists between the nature of the minerals in the fissures and that of the contiguous rocks. When the latter are calcareous, calcite usually forms a conspicuous feature in the veins; among siliceous rocks quartz is abundant. These and the other minerals are for the most part well crystallized or at least largely crystalline in the veins, even when the adjoining rocks are granular or amorphous. They are termed *vein-stones*. Since the joints, faults, and fissures which have been filled with new mineral substances are commonly highly inclined or vertical, mineral veins generally run as steep wall-like bands across the rocks in which they occur. Their minerals are arranged in strips, which on the whole run parallel with the walls of the vein (fig. 58).

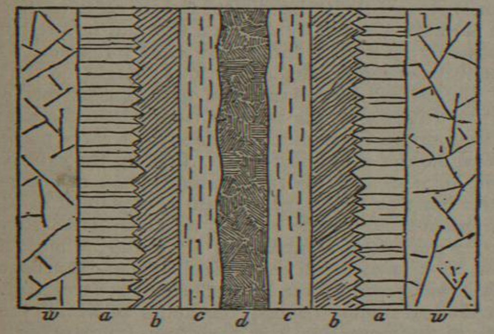

FIG. 58.—*a*, Coating of one mineral, say quartz; *b*, coating of a second mineral, say fluor spar; *c*, coating of first mineral, or of a third, say sulphate of baryta; *d*, rib of ore, as copper or lead; *w*, *w*, walls of the lode.

Mineral veins become *metalliferous*, when among their vein-stones there occur detached crystals or particles, or branching strings and threads, or concretionary masses or parallel bands of native metal, or of the sulphides, oxides, or other ores of metals. The association of these various substances within the two walls or cheeks of a vein is often in a double set of parallel bands, those in one-half of the vein being repeated in the other. The middle of the vein, for example, may consist of galena flanked and partially mixed up with zinc-blende and pyrites. On either side of this central rib there may be a layer of some veinstone, perhaps fluor spar, then a duplicate band of another veinstone, such as barytes or quartz, and so on, to the outer edge of the vein (fig. 58). In other cases, as in auriferous veins of quartz, the vein consists wholly or almost wholly of one vein-stone through which the ore is disseminated in minute grains and strings, so that the vein-stone must be extracted and crushed to obtain the metal by washing.

Mineral veins (*lodes*, *rake-veins*) vary in thickness from only an inch or less up to many fathoms. Extraordinary variations may be traced even in the course of the same vein, a breadth of several feet or yards rapidly diminishing until the two walls nearly or quite meet, to the exclusion of the minerals of the vein. Similar diversities may be observed in the horizontal extent of veins, some being traceable for miles, others disappearing in a few yards.

They sometimes occupy fissures without any throw, but most frequently seem to occur along lines of fault. In some cases indeed it can be shown that dislocation has taken place after some portion of the vein had been formed, but before the completion of the process. They usually send out branches, and in some mining districts do this to such an extent that it becomes hardly possible to identify the main vein among its numerous offshoots.

The direction of the veins varies in different districts. Two series may often be traced,—a principal series running in one general direction, and a minor set crossing the first at right angles or obliquely. Great differences in the richness of a metallic lode may be observed as it is worked vertically and horizontally, some of these depending in a way not easily explained upon the nature of the surrounding rock. Among the Cornish lodes, for example, some contain copper only where they traverse the Devonian slates, and lose it where they enter the granite, where tin takes its place. In the lead tracts of the north of England the metal diminishes where the veins lie in shale, and augments where they run through limestone.

In some rocks, more especially in limestones, large subterranean cavities have been filled with vein-stones and ores. The iron mines of the English lake district, for example, lie in the Carboniferous Limestone, where tunnels and caverns anciently dissolved out of the rock by percolating or running water have been subsequently filled up with hæmatite. In the lead districts of the north of England also, similar cavities have received a plentiful deposit of vein-stones and galena with its accompanying ores.

Various theories have been proposed to account for the infilling of mineral veins. Of these the most noteworthy are—(1) the theory of lateral segregation,—which teaches that the substances in the veins have been derived from the adjacent rocks by a process of solution and redeposit; and (2) the theory of infilling from below,—according to which the minerals and ores were introduced from below dissolved in water or steam or by sublimation, or by igneous fusion and injection.

The fact that the nature and amount of the minerals, and especially of the ores, in a vein vary with the nature of the surrounding rocks seems to show that these rocks have had a certain influence on the precipitation of mineral matter in the fissures passing through them. But that this mineral matter came chiefly from below appears almost certain. The phenomena of the ascent of hot water in volcanic districts afford a close analogy to what has occurred in mineral veins. It is known that at the present time various minerals, including silica, both crystalline and calcedonic, and various metallic sulphides, are being deposited in fissures up which hot water rises. At the same time it is conceivable that to some extent there may be a decomposition of the rocks on either side of a fissure, and that a portion of the mineral matter abstracted may be laid down in another form along the walls of the fissure, or, on the other hand, that the rocks on either side of the fissure may be permeated for some distance by the ascending waters, and that some of the mineral substances carried up in solution may be deposited in the pores and cavities of these rocks as well as in the fissure itself.

### X. Unconformability

Where one series of rocks, whether of aqueous or igneous origin, has been laid down continuously and without disturbance upon another series, they are said to be *conformable*. Thus in fig. 59 the sheets of rock numbered 1, 2, 3, and 4 have succeeded each other in regular order, and exhibit a perfect conformability. They overlap each other, however, No. 2 extending beyond the edge of No. 1, No. 3 beyond that of No. 2, and so on. As already explained (p. 295), this structure points to a gradual subsidence and enlargement of the area of deposit. But all these conformable beds repose against the older platform A, with which they have no direct connexion. That platform may consist of horizontal or inclined strata, or contorted schist, or crystalline igneous rocks. In any case there is a complete break between it and the overlying rocks, which rest successively on different parts of the older mass. This relation is termed an unconformability. The upper conformable beds in fig. 59 are said to lie unconformably upon A.

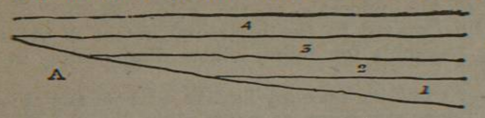

Fig. 59.—Overlap of conformable strata.

It is evident that this structure may occur in ordinary stratified, or in igneous, or in metamorphic rocks, or between any two of these great series. It is most familiarly displayed among stratified masses, and can there be most satisfactorily studied. The lines of bedding furnish a ready means of detecting differences of inclination and discordance of superposition. But even among igneous protrusions and in ancient metamorphic masses, distinct evidence of unconformability is not always difficult to trace.

Though conformable rocks may usually be presumed to have followed each other continuously without any great disturbance of geographical conditions, we cannot always be safe in such an inference. But an unconformability leaves no room to doubt that it marks a decided break in the continuity of deposit. Hence no kind of geological structure is of higher importance in the interpretation of the history of the stratified formations of a country. In rare cases an unconformability may occur between two horizontal groups of strata. In fig. 60, for instance, a set of beds C is shown to lie conformably for some distance upon an older series *d*. Were nothing more to be seen than what appears towards the right hand, we might justifiably conclude the whole of the rocks to be conformable. By passing to the left, however, we should find evidence of the older group having been upraised and unequally denuded before the deposition of the newer. The denudation would show that the conformability was accidental, that the older rocks had really been upraised and worn down before the formation of the newer. In such a case the upheaval must have been so equable as not to disturb the horizontality of the lower rocks.

Fig. 60.—Unconformability among horizontal beds.

As a rule, however, it seldom happens that movements of this kind have taken place over an extensive area so equably as not to produce a want of conformability somewhere between the older and newer rocks. Most frequently the older formations have been disturbed, tilted at various angles, or even placed on end. They have likewise been irregularly and enormously worn down. Hence, instead of lying parallel, the younger beds run transgressively across the upturned denuded ends of the older. The greater the disturbance of the older rocks the more marked is the unconformability. In fig. 61, for instance, the series of beds A is uncomformably covered by the series C. At both sides of the arch the uncomformability is strongly marked, but at the centre *d* the two series seem to be conformable. An unconformability forms one of the great breaks in the geological record. In the foregoing figure, by way of illustration, we see at once that a notable hiatus in deposition, and therefore in geological chronology, must exist between series A and C. The older rocks had been deposited, folded, upheaved, and worn down before the accumulation of the newer series upon their denuded edges. These changes must have demanded a considerable lapse of time. Yet, looking merely at the structure in itself, we have evidently no means of fixing, even relatively, the length of interval marked by an unconformability. The mere violence of contrast between a set of vertical beds below and a horizontal group above it is no reliable criterion of the relative lapse of time between their deposition, for an older portion of a given formation might be tilted on end and be overlaid unconformably by a later part of the same formation. A set of flat rocks of high geological antiquity might, on the other hand, be covered by a formation of comparatively recent date, yet in spite of the want of discordance between the two, they might have been separated by a large portion of the total sum of geological time. It is by the evidence of organic remains that the relative importance of unconformabilities must be measured, as will be explained in part v.

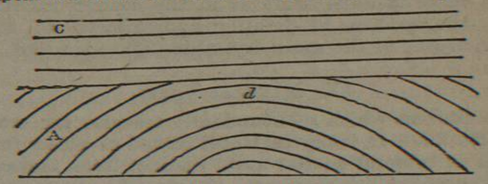

Fig. 61.—Section of unconformable rocks.

Paramount though the effect of an unconformability may be in the geological structure of a country, it must nevertheless be in almost all cases local. The disturbance by which it was produced can have effected but a comparatively circumscribed region, beyond the limits of which the continuity of sedimentation may have been undisturbed. We may therefore always expect to be able to fill up the gaps in one district from the more complete geological formations of another. In fig. 61 we see that something is wanting between A and C. But in the structure of another country or a different part of the same country we might discover the complete succession, as in fig. 62, where the whole of the rocks succeed each other conformably, and where the gap between A and C marked by the unconformability in fig. 61 is bridged over by the intermediate group of strata B.

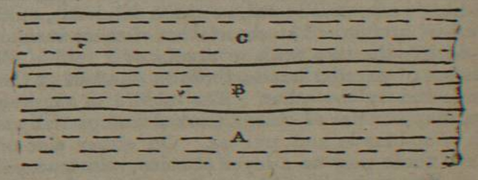

Fig. 62.—Section showing the groups of fig. 61 in conformable sequence, with the intervening blank (B) supplied.

## PART V.—PALÆONTOLOGICAL GEOLOGY.

Palæontology is the science which treats of the structure, affinities, classification, and distribution in time of the forms of plant and animal life embedded in the rocks of the earth's crust. In one sense it may be regarded as a branch of zoology and of botany, its claim in this view to rank as a separate science resting almost solely on the fact that of the forms with which it deals but a small proportion belongs to the living world. In another aspect it may be looked upon as a branch of geology, seeing that its assistance is absolutely indispensable in many of the most familiar and fundamental problems of the latter science. It is under this last aspect that we have to regard it here. We shall consider merely those leading features of palæontological inquiry without some knowledge of which progress in modern geology would be impossible.

*Fossils.*—Palæontological geology, then, deals with the *fossils* or organic remains preserved in the rocks, and endeavours to gather from them information as to the history of the globe and its inhabitants. The term "fossil," meaning literally anything "dug up," was formerly applied indiscriminately to any mineral substance taken out of the earth's crust, whether organized or not. Ordinary minerals and rocks were thus included as fossils. For many years, however, the meaning of the word has been restricted, so as to include only the remains or traces of plants and animals preserved in any natural formation whether hard rock or superficial deposit. The idea of antiquity or relative date is not necessarily involved in this conception of the term. Thus the bones of a sheep buried under gravel and silt by a modern flood, and the obscure crystalline traces of a coral in ancient masses of limestone, are equally fossils.

Nor has the term fossil any limitation as to organic grade. It includes not merely the remains of organisms, but also whatever was directly connected with or produced by these organisms. Thus the resin which was exuded from trees of long-perished forests is as much a fossil as any portion of the stem, leaves, flowers, or fruit, and in some respects is even more valuable to the geologist than more determinable remains of its parent trees, because it has often preserved in admirable perfection the insects which flitted about in the woodlands. The burrows and trails of a worm preserved in sandstone and shale claim recognition as fossils, and indeed are commonly the only indications to be met with of the existence of annelide life among old geological formations. The droppings of fishes and reptiles, called coprolites, are excellent fossils, and tell their tale as to the presence of vertebrate life in ancient waters. The little agglutinated cases of the caddis-worm remain as fossils in formations from which perchance most other traces of life may have passed away. Nay, the very handiwork of man, when preserved in any natural manner, is entitled to rank among fossils; as where his flint-implements have been dropped into the prehistoric gravels of river-valleys, or where his canoes have been buried in the silt of lake-bottoms.

The term fossil, moreover, suffers no restriction as to the condition or state of preservation of any organism. In some rare instances the very flesh, skin, and hair of a mammal have been preserved for thousands of years, as in the case of the mammoths entombed within the frozen mud cliffs of Siberia. In most cases all or most of the original animal matter has disappeared, and the organism has been more or less completely mineralized or petrified. It often happens that the whole organism has decayed, and a mere cast in amorphous mineral matter, as sand, clay, ironstone, silica, or limestone remains; yet all these variations must be comprised in the comprehensive term fossil.

*Conditions for the Preservation of Organic Remains.*—At the outset the question naturally suggests itself how the remains of plants and animals come to have been preserved in rocks at all. If we observe what takes place at the present day, and argue that it may fairly be taken as an indication of what has been the ordinary condition of things in the geological past, we see that there must have been so many chances against the conservation of either animal or plant remains that their occurrence among stratified formations should be regarded as exceptional, and as the result of various fortunate accidents.

I. Consider, in the first place, what chances exist for the preservation of remains of the present fauna and flora of a country. The surface of the land may be densely clothed with forest, and abundantly peopled with animal life. But the trees die and moulder into soil. The animals, too, disappear, generation after generation, and leave no perceptible traces of their existence. If we were not aware from authentic records that central and northern Europe was covered with vast forests at the beginning of our era, how could we know this fact? What has become of the herds of wild oxen, the bears, wolves, and other denizens of primeval Europe? How could we prove from the examination of the surface soil of any country that those creatures had once abounded there? We might search in vain for any such superficial traces, and would learn by so doing that the law of nature is everywhere "dust to dust."

The conditions for the preservation of any relics of the plant and animal life of a terrestrial surface must therefore be always exceptional. They are supplied only where the organic remains can be protected from the air and superficial decay. Hence they may be observed in

1. *Lakes.*—Over the floor of a lake deposits of silt, peat, marl, &c., are formed. Into these the stems, branches, leaves, flowers, fruits, or seeds of plants from the neighbouring land may be carried, together with the bodies of land animals, insects, and birds. An occasional storm may blow the lighter debris of the woodlands into the water. Such portions of the wreck as did not float, and were not washed ashore again, might sink to the bottom. Of these the larger part would in most cases probably rot away, so that, in the end, only a very small fraction of the whole vegetable matter cast over the lake by the wind would be covered up and preserved at the bottom. In like manner the animal remains swept by winds or by river floods into the lake would run so many risks of dissolution that only a proportion of them, and probably merely a small proportion, would be preserved. When we consider these chances against the conservation of the vegetable and animal life of the land, we must admit that, at the best, lake-bottoms can contain but a meagre and imperfect representation of the abundant life of the adjacent hills and plains.

But lakes have a distinct flora and fauna of their own. Their aquatic plants may be entombed in the gathering deposits of the bottom. Their mollusks, of characteristic types, sometimes form, by the accumulation of their remains, sheets of soft calcareous marl, in which many of the undecayed shells are preserved. Their fishes, likewise distinctly lacustrine, no doubt must often be entombed in the silt or marl.

2. *Peat-mosses.*—Wild animals venturing on the more treacherous watery parts of a peat-bog are sometimes engulphed or "laired." The antiseptic qualities of the peat preserve such remains from decay. Hence from European peat-mosses numerous remains of deer and oxen have been exhumed. Evidently the larger beasts of the forest ought chiefly to be looked for in these localities.

3. *Deltas at River Mouths.*—From what has been said in previous pages (*ante*, pp. 276–8) regarding the geological operations of rivers, it is obvious that to some extent both the flora and the fauna of the land may be buried among the sand and silt of deltas. When we consider, however, that though occasional or frequent river-floods sweep dow